MICROWAVE IMAGING FOR THE DETECTION AND LOCALIZATION OF BREAST TISSUE MALIGNANCIES USING TIME REVERSAL BEAMFORMING

by

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CERTIFICATE

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Md Delwar Hossain

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Mathematical Notations

- $(.)^*$ denotes complex conjugate
- $(.)^T$ denotes transpose for a vector or matrix
- $(.)^H$ denotes Hermitian transpose for a vector or matrix
- $||.||$ denotes Frobenius norm for a vector or matrix
- $tr(.)$ denotes trace of a matrix
- $vec(.)$ forms a vector by sequentially stacking the columns of a matrix
- $vecd(.)$ forms a vector from the diagonal elements of a matrix
- $vec\bar{D}(.)$ forms a vector from diagonal elements of each dyad of a dyadic vector
- $\overline{(.)}$ denotes a dyadic vector or matrix
- $\Re\{.\}$ indicates real part of a vector matrix of scalar
- $\mathcal{R}(.)$ indicates range of a matrix
- $E\{.\}$ denotes expectation operator
- Rank(.) denotes rank of a matrix
- $\oplus$ denotes direct sum
- $*$ denotes convolution
- $\otimes$ denotes Kronecker product between two vectors or matrices
- $\odot$ denotes Khatri-Rao product between two matrices
- $ceil(.)$ denotes round up to the nearest integer

List of Symbols

E	Electric field
H	Magnetic field
J	Current density
$\mathcal{D}$	Electric flux density
$\mathcal{B}$	Magnetic flux density
c	Free space electromagnetic wave velocity
ω	Angular frequency
ε_r	Relative permittivity
ε_0	Free space permittivity
μ	Permeability
μ_0	Free space permeability
σ	Conductivity
σ^2	noise variance
λ	Wavelength
k	Wave number
γ	Lagrange multiplier
w	Array weight vector
a	Array steering vector

$\mathbf{B}$	Beamspace processing matrix
$\mathbf{B}_{bp}$	Beamspace back propagation beamformer
$\boldsymbol{\beta}$	Beamforming gain
$\boldsymbol{\Gamma}$	Projection operator for beamspace processing
$\bar{\boldsymbol{\chi}}$	Target scattering tensor matrix
$\bar{x}$	Target scattering tensor
$\boldsymbol{\tau}$	Scattering strength matrix 2-D target
τ	Scattering strength of 2-D target
G	Green's function
$\mathbf{g}$	Green's function vector
$\mathcal{G}$	Green's function vector matrix
$\mathbf{R}$	Array covariance matrix
$\mathbf{F}$	Array sampling matrix
$\mathbf{K}$	Multistatic matrix
$\mathbf{T}$	Time reversal operator
$\mathbf{U}$	Left singular vector matrix
$\mathbf{V}$	Right singular vector matrix
$\mathbf{v}$	Right singular vector/eigen vector
$\boldsymbol{\Sigma}$	Singular value matrix

$\boldsymbol{\Sigma}^{\mathcal{S}}$	Signal subspace (significant) singular value matrix
$\boldsymbol{\Sigma}^{\mathcal{N}}$	Noise subspace (insignificant) singular value matrix
$\mathbf{g}_B$	Beamspace green's function vector
$\boldsymbol{\mathcal{G}}_B$	Beamspace green's function vector matrix
$\mathbf{K}_B$	Beamspace multistatic matrix
$\mathbf{T}_B$	Beamspace time reversal operator
$\mathbf{U}_B$	Beamspace left singular vector matrix
$\mathbf{V}_B$	Beamspace right singular vector matrix
$\mathbf{v}_B$	Beamspace right singular vector/eigen vector
$\boldsymbol{\Sigma}_B$	Beamspace singular value matrix
$\mathbf{V}^{\mathcal{N}}$	Noise subspace of time reversal operator
$\mathbf{V}^{\mathcal{S}}$	Signal subspace of time reversal operator
$\mathbf{V}_B^{\mathcal{N}}$	Beamspace time reversal operator noise subspace
$\mathbf{V}_B^{\mathcal{S}}$	Beamspace time reversal operator signal subspace
$\boldsymbol{\mathcal{I}}$	Fisher information matrix
$\mathbf{P}_{\mathbf{A}}$	Projection operator for **A**
$\mathbf{Z}_C$	Coherent signal subspace method focusing matrix
$\mathbf{Z}_W$	Wavefield modelling method focusing matrix
$\mathbf{T}_C$	Coherent signal subspace method time reversal operator

$\mathbf{T}_W$	Wavefield modelling method time reversal operator
$\mathbf{V}_C^{\mathcal{S}}$	Signal subspace of $\mathbf{T}_C$
$\mathbf{V}_C^{\mathcal{N}}$	Noise subspace of $\mathbf{T}_C$
$\mathbf{v}_c$	Eigen vector of $\mathbf{T}_C$
$\mathbf{T}_{CB}$	Coherent beamspace time reversal operator
$\mathbf{V}_{CB}^{\mathcal{S}}$	Signal subspace of $\mathbf{T}_{CB}$
$\mathbf{V}_{CB}^{\mathcal{N}}$	Noise subspace of $\mathbf{T}_{CB}$
$\mathbf{v}_{CB}$	Eigen vector of $\mathbf{T}_{CB}$
H_0^1	Zero-th order Hankel function of first kind
J_m	Bessel function of first kind and order m
j_m	Spherical Bessel function of first kind and order m
Y_{lm}	Spherical harmonics of degree l and order m

List of Abbreviations and Acronyms

2-D	Two dimensional
3-D	Three dimensional
C1	Class 1 mostly fatty breast
C2	Class 2 breast with scattered density
C3	Class 3 heterogeneously dense breast
C4	Class 4 highly dense breast
FDTD	Finite difference time domain
PML	Perfectly matched layer
ABC	Absorbing boundary condition
TOA	Time of arrival
DOA	Direction of arrival
TR	Time reversal
SEER	Surveillance, Epidemiology, and End Results
ULA	Uniform linear array
UCA	Uniform circular array
UWB	Ultrawideband
SVD	Singular value decomposition
EVD	Eigen value decomposition

SV	Singular value
CWT	Continuous wavelet transform
LOS	Line of sight
TRO	Time reversal operator
DORT	Decomposition of the time reversal operator
TR-MUSIC	Time reversal multiple signal classification
SCB	Standard Capon beamformer
RCB	Robust Capon beamformer
MVB	Minimum variance beamformer
MVDR	Minimum variance distortionless response
TR-SCB	Time reversal standard Capon beamformer
TR-RCB	Time reversal robust Capon beamformer
TM	Transverse magnetic
TR-MVB	Time reversal minimum variance beamformer
TR-MV-EPC	TR-MV beamformer with environment perturbation constraints
AWGN	Additive white Gaussian noise
SNR	Signal to noise ratio
AIC	Akaike information criterion
MDL	Minimum description length

PSLR	Peak to side lobe ratio
B-TRO	Beamspace TRO
B-DORT	Beamspace DORT
B-TR-MUSIC	Beamspace TR-MUSIC
B-TR-RCB	Beamspace TR-RCB
FFT	Fast Fourier transform
DFT	Discrete Fourier transform
ML	Maximum likelihood
TR-ML	Time reversal maximum likelihood
B-TR-ML	Beamspace time reversal maximum likelihood
CRLB	Cramer Rao Lower Bound
FIM	Fisher information matrix
CSSM	Coherent signal subspace method
WMM	Wavefield modelling method
CS-TRO	Coherent TRO using coherent signal subspace method
CW-TRO	Coherent TRO using wavefield modelling method
CS-TR-RCB	CSSM for TR-RCB
CW-TR-RCB	WMM for TR-RCB
B-CS-TRO	Beamspace processing for CSSM TRO
B-CS-DORT	Beamspace processing for CS-DORT

B-CS-TR-MUSIC	Beamspace processing for CS-TR-MUSIC
CS-B-TRO	CSSM focusing for B-TRO
CS-B-DORT	CSSM focusing for B-DORT
CS-B-TR-MUSIC	CSSM focusing for B-TR-MUSIC
CS-B-TR-ML	CSSM focusing for B-TR-ML
RMSE	Root Mean Square Error
pdf	Probability density function

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ABSTRACT

Breast cancer is the most common cancer suffered by Australian women. Early detection of cancer provides the best chance of survival to the victims. Microwave imaging has shown the potential to be a complimentary imaging modality to the existing breast cancer imaging techniques such as mammography, MRI and ultrasound. Microwave imaging can overcome the drawbacks of conventional imaging techniques such as patient discomfort and ionizing radiation hazard. The principle of microwave imaging for breast cancer detection is based on the dielectric property contrast between healthy breast tissues and malignant tissues. However, in dense breasts that have high amounts of dense fibro-glandular tissue content, the dielectric property contrast between tumor and surrounding healthy glandular tissues can be quite low. To overcome the problems arising from imaging in low contrast scenario, contrast enhancing agents and hybrid imaging modalities have been proposed in the literature. But, such complex modalities not only complicate the screening process but also add to patients discomfort and cost. Moreover, such techniques may still fail to detect multiple tumors unambiguously in highly dense breasts.

In this thesis, we investigate the use of computational time reversal imaging techniques for breast cancer detection and localization using anatomically realistic numerical breast phantoms. Both radar imaging and tomography imaging techniques have been applied for breast cancer detection. Microwave tomography cannot detect abrupt change in dielectric properties when contrast is low. On the other hand radar imaging can reveal the target location information even under low contrast scenario but suffers from clutter and noise in the medium. Time reversal microwave imaging

can be considered to be a variant of radar imaging. Time reversal uses medium heterogeneity as an advantage and is highly suitable for imaging in heterogeneous medium. However, the performance of time reversal can also be affected by low dielectric property contrast between target and surrounding tissue clutter. To overcome the effects of clutter interference on target detection and localization, in this thesis, we propose novel beamforming techniques for time reversal microwave imaging. Firstly, we extend beamspace processing for time reversal imaging technique with an aim to reduce clutter effects and improve robustness of imaging. However, when we use ultra-wideband microwave pulses for imaging, a coherent approach is necessary to overcome problems due to random phase variations arising in each frequency bin. We propose two different novel coherent beamspace time reversal imaging techniques for breast cancer screening. The focusing matrix based coherent signal subspace processing is found to be more suitable for subspace and maximum likelihood based time reversal imaging techniques whereas the focusing matrix based on wavefield modelling method is found more suitable for time reversal minimum variance imaging. We propose to combine coherent focusing with beamspace processing (C-B) to obtain superior imaging localization performance. We have also derived Cramer Rao Lower Bound (CRLB) for beamspace time reversal imaging. We have proposed Coherent beamspace DORT (C-B-DORT), C-B-TR-MUSIC, C-B-TR-RCB, C-B time reversal maximum likelihood (C-B-TR-ML) methods to detect small single and multiple tumors in highly dense breasts where conventional techniques are prone to fail. Our investigations have revealed that C-B-TR-ML imaging has superior performance compared to other techniques in detecting three small sized tumors embedded in a highly dense breast phantom.